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Gaussian pigeon-inspired optimization approach to orbital spacecraft formation reconfiguration

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Abstract With the rapid development of space technology, orbital spacecraft formation has received great attention from international and domestic academics and industry. Compared with a single monolithic, the orbital spacecraft formation system has many advantages. This paper presents an improved pigeon-inspired optimization (PIO) algorithm for solving the optimal formation reconfiguration problems of multiple orbital spacecraft. Considering that the uniform distribution random searching system in PIO has its own weakness, a modified PIO model adopting Gaussian strategy is presented and the detailed process is also given. Comparative experiments with basic PIO and particle swarm optimization (PSO) are conducted, and the results have verified the feasibility and effectiveness of the proposed Gaussian PIO (GPIO) in solving orbital spacecraft formation reconfiguration problems.

1. Introduction

Orbital spacecraft formation is the concept that multiple spacecraft work together to achieve a common mission. Coordinating orbital spacecraft formation has more benefits than single spacecraft, including faster build time, easier launch, cheaper replacement and the ability to view research targets from multiple angles or at multiple times. These qualities make them ideal for astronomy, meteorology, communications, earth science, environmental uses and even military uses.

This problem can be solved in terms of convex optimization and some other approaches have been proposed to obtain optimal control strategies for reconfiguration on other vehicles in literature. In Ref. [1], closed-loop brain storm optimization is used to work out the optimal satellite formation reconfiguration problem. In Ref. [2], a new formation reconfiguration technology is applied in other autonomous vehicles, which has a particularly instructive inspiration for spacecraft formation. In terms of controlling the spacecraft formation, an ideal autonomous attitude coordinated controller, a robust adaptive attitude coordinated controller and a filtered robust adaptive attitude coordinated controller are proposed to deal with the issue in Ref. [3]. A method for fuel-optimal trajectories considering collision avoidance designing is discussed based on mix-integer linear programming in Ref. [4]. Inalhan et al.[5] studied relative dynamics and the spacecraft formation controlling system in eccentric orbits. Furthermore, in Ref. [6], an analytical

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fuel-optimal impulsive formation reconfiguration strategy from the perspective of relative orbital elements is presented.

Swarm intelligence optimization has obtained increasing attention from researchers in the last two decades. Some optimization algorithms have been proposed and studied during these years, including particle swarm optimization (PSO),[7,8] ant colony optimization (ACO),[9] brain storm optimization (BSO)[10] and the artificial bee colony (ABC) algorithm.[11] In Ref. [12], co-evolutionary PSO is used on satellites' formation reconfiguration. Although these optimization algorithms have remarkable performance in solving optimization problems, there is also large room for improvement in terms of the convergence rate and global searching abilities. The pigeon-inspired optimization (PIO) algorithm is a novel swarm intelligence algorithm, which was firstly proposed by Duan and Qiao in 2014.[13] It can accelerate the convergence speed impressively. Thus this paper will adopt the PIO as a research target.

Although PIO solves the convergence rate problem, the ability of global searching is still not optimistic. In order to overcome this weakness in PIO, a Gaussian item is introduced to balance the importance between exploration and exploitation results. In this paper, this Gaussian PIO algorithm (GPIO) is used for optimal trajectory design in cooperative orbital spacecraft formation reconfiguration, namely, to design an optimal route for the spacecraft when they need to reach a new formation required for different missions. For the reason that the lifetime of spacecraft is limited, one of the most important constraints for the optimal trajectory is overall fuel cost minimization. The other two constraints are easy to understand, that is, collision avoidance and final configuration.[1] Specifically, the collision avoidance is the basic requirement and has to be satisfied at any time.

2. Problem formulation

In order to apply the swarm intelligence optimization algorithms to solve the complex dynamic problems, the orbital spacecraft formation reconfiguration problem has to be simplified. This section aims at formulating the spacecraft formation reconfiguration problem so that the parameters in the algorithm can be obtained easily.

2.1. Coordinate system

The length of the orbital spacecraft can be ignored compared with the distance between two spacecrafts. According to the relative motion dynamics, each spacecraft can be modeled as one mass point. The coordinate system is shown in Fig. 1. The reference spacecraft is represented by L, which means the leader spacecraft, and F represents the follower spacecraft. The x coordinate is in the radial direction, y-axis is in the in-track direction, and the z component is in parallel with the angular momentum direction.

2.2. Dynamics model

In this paper, three fundamental assumptions have to be satisfied[14]:

(1) Assume that the Earth is a homogeneous globe and ignore any perturbation.

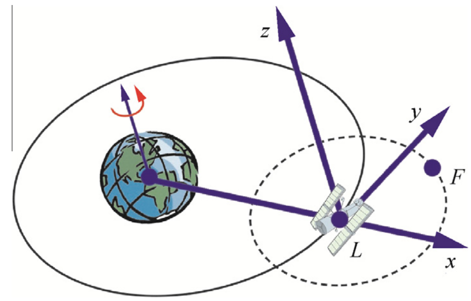

Fig. 1 Coordinate system.

(2) The eccentricity of the orbital spacecraft orbit, including the reference spacecraft and the follower ones, should be equal to zero.

(3) The distance between the reference spacecraft and the follower spacecraft is much less than the orbit radius.

To describe the relative motion between the spacecraft, Hill's equation, which is also known as Clohessy-Wiltshire (CW) equation,[3] is the most widely used approximation based on the fundamental assumptions mentioned above. Generally, it can be expressed as

$$\begin{cases} \ddot{x} = 2\omega\dot{y} + 3\omega^2 x + u_x \\ \ddot{y} = -2\omega\dot{x} + u_y \\ \ddot{z} = -\omega^2 z + u_z \end{cases} \tag{1}$$

where x, y and z are the F coordinates in the above coordinate system; u_x, u_y and u_z are the control inputs in x-axis, y-axis and z-axis directions, respectively; ω is the average orbit angular velocity.

2.3. Two-impulse control mathematical model

In order to describe the complex motion of the orbital spacecraft formation with the Hill's equation, the orbital spacecraft formation reconfiguration is supposed to satisfy the three constraints. First, the orbit of the reference spacecraft has to be in the shape of a circle or an approximative circle. Second, in the two-impulse control mathematical model, the whole power for the follower spacecraft should be originated from these two impulses. In other words, during the spacecraft formation reconfiguration process, only the predesigned two impulses provide the power. Third, the error of the follower spacecraft's relative position can be ignored by comparing with the distance between the spacecraft.[14] Under these assumptions, the control inputs u_x, u_y and u_z in Eq. (1) are equal to zero. Thus

$$\begin{cases} x(t) = \dfrac{\dot{x}_0}{\omega}\sin(\omega t) + \left(-3x_0 - \dfrac{2\dot{y}_0}{\omega}\right)\cos(\omega t) + 2\left(2x_0 + \dfrac{y_0}{\omega}\right) \\ y(t) = 2\left(3x_0 + \dfrac{2\dot{y}_0}{\omega}\right)\sin(\omega t) + \dfrac{2\dot{x}_0}{\omega}\cos(\omega t) - 3(2\omega x_0 + \dot{y}_0)t \\ \qquad + \left(y_0 - \dfrac{2\dot{x}_0}{\omega}\right) \\ z(t) = \dfrac{\dot{z}_0}{\omega}\sin(\omega t) + z_0\cos(\omega t) \end{cases} \tag{2}$$

where $x_0, y_0, z_0, \dot{x}_0, \dot{y}_0$ and $\dot{z}_0$ are the initial states of the spacecraft.